

Ages and Chemical Abundances in Dwarf Spheroidal Galaxies

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Abstract. The dwarf spheroidal galaxies (dSphs) in the Local Group are excellent systems on which we can test theories of galaxy formation and evolution. Color-magnitude diagrams (CMDs) containing many thousands of stars from the asymptotic giant branch to well below the oldest main-sequence turnoff are being used to infer their star-formation histories, and surprisingly complex evolutionary histories have been deduced. Spectroscopy of individual red giant stars in the dSphs is being used to determine the distribution of chemical abundances in them. By combining photometry and spectroscopy, we can overcome the age-metallicity degeneracy inherent in CMDs and determine the evolution of dSphs with unprecedented accuracy. We report on recent progress and discuss a new and exciting avenue of research, high-dispersion spectroscopy that yields abundances for numerous chemical elements. The latter allows us to estimate the enrichment from both Type Ia and Type II supernovae (SNe) and places new limits on how much of the Galaxy could have been accreted in the form of dSph-sized fragments and when such mergers could have taken place.

1. Introduction

We begin with a review of the typical physical characteristics of a dSph galaxy. DSphs have low total luminosities ($-9 \geq M_V \geq -14$) and small physical sizes (core radii ≈ 200 to 600 pc). They are stellar systems with little or no detectable interstellar medium. Upper limits on the mass of HI inside the optical radius are typically $< 10^4 M_\odot$ (Young 1999, and references therein). However, Carignan

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et al. (1998) recently discovered at least $3 \times 10^4 M_\odot$ of HI lying just outside the optical radius of the Sculptor dSph. Additional searches should be made for gas surrounding the Fornax and Leo I dSphs, which have very young stars, ~ 0.1 Gyr and 1 Gyr, respectively, in their CMDs (Stetson, et al. 1998, Gallart, et al. 1999). The dSphs in the Local Group are nearby and diffuse (central surface densities ≈ 0.1 to $1 M_\odot/\text{pc}^2$), which makes them very amenable to photometric studies.

Low total masses (10^7 to $10^9 M_\odot$) have been inferred for dSphs from their small central stellar velocity dispersions (7 to 14 km/s). (See Mateo 1998 for a recent review.) The masses are usually inferred assuming mass follows light. However, if dark matter halos are more extended than the luminous galaxies, as is probably the case, then these are only lower limits to the total mass. Whether or not the mass inside the optical radius is dominated by stars or dark matter is a function of galaxy luminosity (Mateo 1998). The derived mass-to-light ratios vary from $M/L_V = 5$ (in solar units) for the Fornax dSph ($M_V = -14$) to $M/L_V = 200$ for the Draco dSph ($M_V = -9$). The former being only slightly larger than the $M/L_V = 4$ expected for an old stellar population, and the later indicating a mass dominated by dark matter. The physical cause of the clear trend in M/L_V versus L_V is an open question. Differences in total mass or concentration of the dark matter halos could make some dSphs more susceptible to loosing gas in supernova-driven galactic winds and thus less efficient at converting their gas into stars.

2. Star-Formation Histories

Great strides have been made recently in quantifying the ages of stars in dSphs through CMD analysis because of the increased availability of wide-field CCD cameras on 4-meter class telescopes and the high angular resolution of WFPC2 on the Hubble Space Telescope. Two examples are shown in Figure 1. Much to our initial surprise, we found most of the dSphs in the Local Group have had complex star-formation histories! (See Smecker-Hane 1997 for a recent review.) Nearly all of the dSphs began forming stars ~ 14 Gyr ago during the epoch of globular cluster formation in our Galaxy. Some dSphs lost their gas and stopped forming stars relatively quickly (Ursa Minor: Hernandez, et al. 1999; Draco: Grillmair, et al. 1998), some dSphs continued forming stars for many Gyr (Leo II: Mighell & Rich 1996, Carina: Smecker-Hane, et al. 1999a, Hurley-Keller, et al. 1998), other dSphs continued to vigorously form stars until only 1 or 2 Gyr ago (Fornax: Stetson, et al. 1998; Leo I: Gallart, et al. 1999). Carina is a particularly intriguing dSph because it stopped forming stars for a few Gyr (~ 7 to 10 Gyr ago) after which star formation resumed again for another few Gyr (~ 7 to 4 Gyr ago). Thus most of the dSphs formed stars over many dynamical timescales (few $\times 0.1$ Gyr) despite their low velocity dispersions (~ 10 km/s). They were able to retain and recycle gas even though thousands of SNe exploded in them. A key observation may be that dSphs form stars slowly. It may be that massive stars, through photoionization and stellar winds, expand networks of bubbles and tunnels through the interstellar medium (ISM) so the hot ejecta from SNe quickly escapes the galaxy without imparting much kinetic energy to

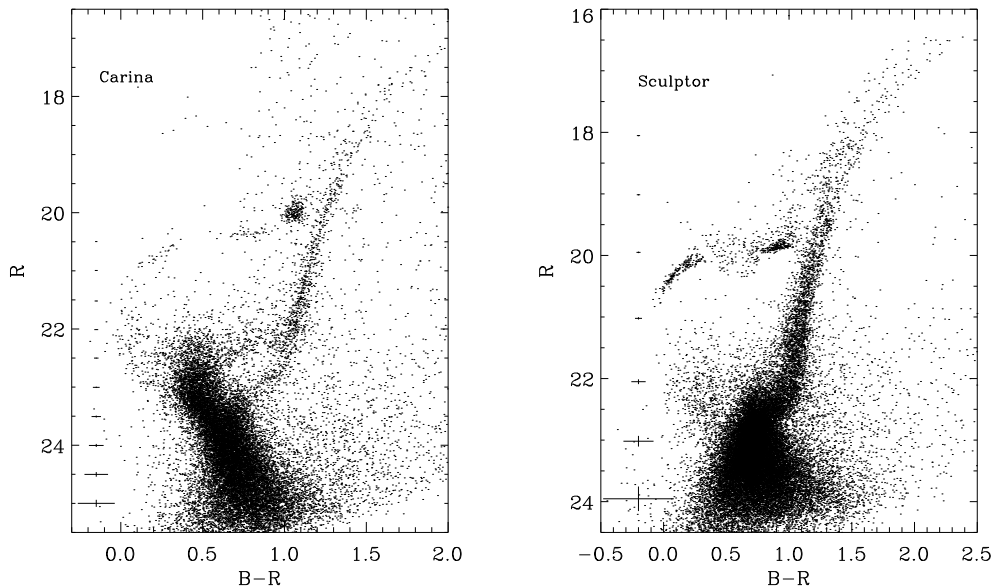


Figure 1. CMDs for the Carina dSph (left; Smecker-Hane, et al. 1999a) and the Sculptor dSph (right; Smecker-Hane, et al. 1999b) obtained with the CTIO 4.0-meter telescope.

the ISM (e.g. Lin & Murray 1993). Thus dSphs may be teaching us that star formation is self-regulated even in the lowest mass galaxies.

3. Chemical Abundances

Measuring the chemical abundances of the stellar populations in dSphs through spectroscopy of individual red giant stars will be crucial for constraining the inflow and outflow of gas from these galaxies. (For example, was star formation in Carina renewed by infall of fresh gas, or did gas remain gravitationally bound the dSph but was temporarily suspended from cooling and forming stars by something such as the intra-galactic UV background?) Independently determining the metallicities of the stars via spectroscopy also gives us the ability to overcome the age-metallicity degeneracy inherent in CMDs and enables us to infer unique and accurate solutions for star-formation histories.

Studies of the chemical abundances of stars in dSphs have been made, but the next few years will be particularly fruitful because of the wide availability of multi-fiber spectrographs. The method most commonly used to measure metallicities of red giant stars in dSphs is the reduced equivalent width of the calcium infrared triplet (see Rutledge, et al. 1997, and references therein). This method is preferred because relative metallicities accurate to 0.1 dex can be obtained for spectra with moderate resolution ($R \approx 3500$) and moderate signal-to-noise ratio ($S/N \approx 30$). DSphs have low mean metallicities, $[\text{Fe}/\text{H}] \approx -2.0$ dex, although each dSph has a significant internal metallicity dispersion approximately described by a Gaussian with $\sigma \simeq 0.25$ dex with the full range in metallicities

spanning ~ 1.0 dex (Draco: Lehnert, et al. 1992, Sextans: Suntzeff, et al. 1993, Carina: Smecker-Hane, et al. 1999c). This implies recycling of SNe ejecta and an extended period of star formation (> 0.1 Gyr) for even the Draco dSph, which contains primarily ~ 14 Gyr old stars.

4. Chemical Abundance Ratios

The complex star-formation histories inferred for most dSphs should leave obvious signatures in the chemical element ratios of their stars. Consider a delta-function burst of star formation. Type II SNe will explode after $< \text{few} \times 10^7$ yr, and enrich the ISM with a high fraction of α elements (e.g. O, Ca, Mg, Si, Ti) relative to Fe-peak elements (e.g. Fe, Cr, Ni). For example, the IMF-averaged yield from Type II SNe has $[\text{Ca}/\text{Fe}] = +0.41$ (Timmes, et al. 1995). In contrast, Type Ia SNe begin exploding approximately 0.1 Gyr after the stars form and continue for many Gyr. However, their ejecta is dominated by Fe-peak elements. The yield of Type Ia SNe has $[\text{Ca}/\text{Fe}] = -0.31$ (Thielemann, et al. 1986). This has interesting consequences for constraining how much of the Galaxy could be built through accretion of dwarf-galaxy sized fragments, and when such mergers could have occurred. For example, typical Galactic halo stars have $[\alpha/\text{Fe}]$ approximately equal to the Type II SNe yields (see McWilliam 1997, and references therein). Thus the Galactic halo has been inferred to have formed quickly because only ejecta from short-lived Type II SNe, and not from long-lived Type Ia SNe, were incorporated into halo stars.

The Sagittarius (Sgr) dSph was recently discovered to be merging with the Galaxy (Ibata, et al. 1997), although how fast this merger is proceeding is debated. At a distance of a only 24 kpc, Sgr dSph stars are amenable to high-dispersion spectroscopy and abundances of numerous chemical species can be measured. We obtained echelle spectra with HIRES (Vogt, et al. 1994) on the Keck I telescope for 14 stars in the Sgr dSph that span a wide range of age and metallicity as inferred from their position the CMD (Sarajedini & Layden 1995). Our echelle spectra cover 5200 to 7600 Å and have high resolution ($R = 43000$) and high signal-to-noise ratios (40 to 80). The spectra were reduced with the standard IRAF ECHELLE package, and equivalent widths for approximately 270 absorption lines were measured with our GETJOB program (McWilliam, et al. 1995). A sample spectrum is shown in Figure 2.

To derive chemical abundances, we use model atmospheres from Kurucz (1992) and a heavily modified version of MOOG (Snedden 1973). We began by adopting initial effective temperatures (T_{eff}) and gravities ($\log g$) determined from VIJK-band photometry. However the final stellar parameters are determined self-consistently from the model atmosphere analysis. We set $\log g$ by requiring consistency between the abundances derived from Fe I and Fe II lines, T_{eff} by requiring abundances derived from Fe I lines be independent of excitation potential, and the microturbulence by requiring abundances derived from Fe I lines be independent of equivalent width. (Differences between initial and final T_{eff} values ranged from 0 to 300 °K.) The preliminary abundance results for our first 11 stars are shown in Table 1. The mean $1 - \sigma$ measurement errors are typically 0.05 dex for $[\text{Fe}/\text{H}]$ and 0.1 dex for $[\text{X}/\text{Fe}]$. We are investigating potential non-LTE effects on the Ti abundances derived for the 2 most metal-

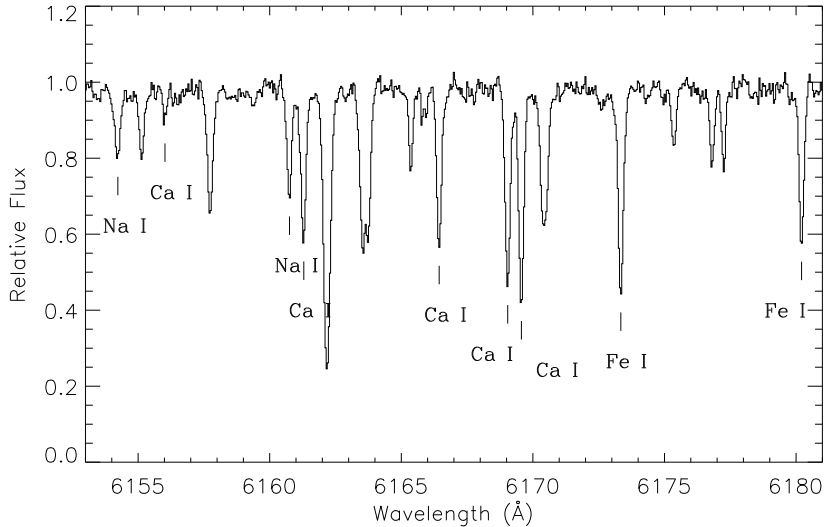


Figure 2. A section of the echelle spectrum of Sagittarius dSph star #1-73, whose abundances are $[\text{Fe}/\text{H}] = -1.41$ and $[\text{Ca}/\text{Fe}] = +0.21$.

poor stars. We also will derive abundances for neutron-capture elements such as Eu, Ba and La, whose line profiles are non-Gaussian because of hyper-fine splitting, through spectral synthesis.

In a similar study, Brown, et al. (1999) obtained echelle spectra at lower resolution ($R = 24000$) with the CTIO 4-meter telescope for 2 of the brightest red giants in the globular cluster M54, a member of the Sgr dSph. Also, Shetrone, et al. (1998) obtained lower signal-to-noise ($S/N = 27$) spectra with HIRES on the Keck I telescope for 4 stars in the Draco dSph.

Figure 3 illustrates the variation of $[\text{Ca}/\text{Fe}]$ with metallicity for dSphs stars, and Figure 4 shows the same for Galactic stars. (Other α elements show similar behaviour.) Surprisingly, the trend of $[\alpha/\text{Fe}]$ with $[\text{Fe}/\text{H}]$ for the Sgr dSph more resembles that of the Galactic disk than the Galactic halo! The relatively smooth trend ending with stars having solar metallicity and solar element ratios implies a long, continuous rather than episodic, star-formation history. Seventy-five percent of the iron in stars with $[\text{Ca}/\text{Fe}] = 0$ was synthesized in Type Ia SNe. Thus the star-formation rate and chemical evolution of the Sgr dSph was complex. We suggested the solar metallicity red giants in the Sgr dSph were very young, ~ 1 Gyr old, and Bellazzini, et al. (1999) have recently found the possible main-sequence counter parts of these red giants in their CMD. Note that the current metallicity of the Large Magellanic Cloud is significantly lower, $[\text{Fe}/\text{H}] \approx -0.3$, than the most metal-rich stars in the Sgr dSph even though the LMC is approximately 45 times more luminous than the Sgr dSph! Could this mean a large fraction of Sgr dSph's stars were stripped away recently, or does the Sgr dSph accrete gas from the Galactic disk when it plunges through it? Dynamical arguments seem to disfavor both ideas leaving us to hypothesize that the core of the dark matter halo may be massive enough for star formation to continue in the central regions while the lower-density outer regions are slowly peeled away.

Table 1. Preliminary chemical abundances derived for Sagittarius dSph stars (Smecker-Hane & McWilliam 1999). The adopted solar abundances are the meteoric values from Anders & Grevesse (1989).

STAR	Fe/H	O/Fe	Na/Fe	Al/Fe	Ca/Fe	Si/Fe
1-87	-1.41	+0.19	-0.08	-0.01	+0.31	+0.20
1-73	-1.14	-0.82	+0.23	+1.20	+0.21	+0.50
1-150	-0.59	-0.08	-0.53	-0.33	+0.06	+0.02
1-245	-0.59	-0.00	-0.32	+0.13	+0.10	+0.10
2-38	-0.57	-0.07	-0.56	-0.27	+0.08	-0.03
1-229	-0.52	-0.19	-0.51	-0.38	-0.04	+0.07
1-242	-0.40	-0.14	-0.31	-0.30	-0.14	+0.16
2-75	-0.37	-0.09	-0.31	-0.17	+0.08	-0.02
1-95	-0.26	+0.08	-0.37	-0.24	-0.11	+0.00
1-267	-0.06	-0.20	-0.51	-0.41	-0.03	+0.08
2-85	-0.03	+0.00	-0.34	-0.33	+0.03	+0.05

STAR	Fe/H	TiI/Fe	TiII/Fe	Cr/Fe	Ni/Fe
1-87	-1.41	+0.14	+0.43	+0.05	-0.09
1-73	-1.14	-0.09	+0.49	+0.03	+0.01
1-150	-0.59	-0.17	—	-0.20	-0.09
1-245	-0.59	-0.07	+0.10	—	-0.17
2-38	-0.57	-0.01	-0.01	-0.14	-0.14
1-229	-0.52	-0.09	+0.05	-0.18	-0.18
1-242	-0.40	+0.02	+0.33	—	-0.09
2-75	-0.37	+0.11	+0.01	-0.16	-0.06
1-95	-0.26	+0.08	+0.15	—	—
1-267	-0.06	+0.04	+0.04	-0.05	+0.00
2-85	-0.03	-0.03	-0.06	—	-0.14

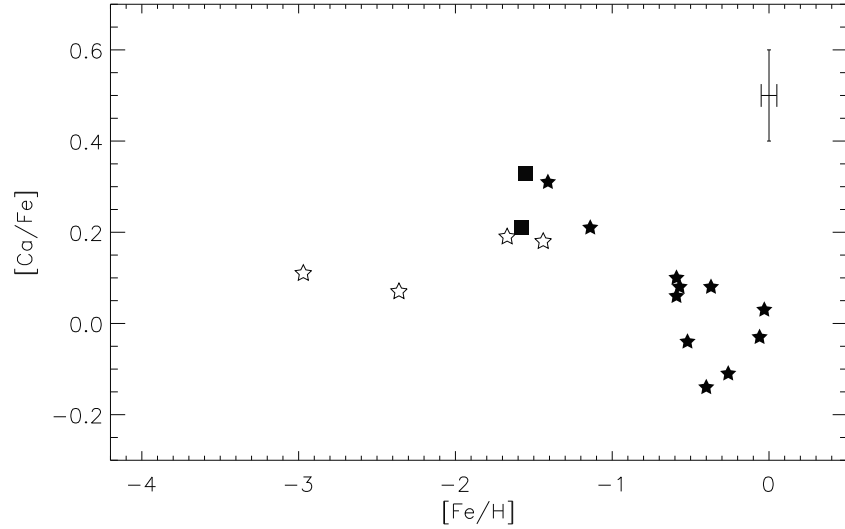


Figure 3. Calcium to iron abundance ratio as a function of metallicity for dSph stars: *solid stars* for Sgr dSph field stars from Smecker-Hane, et al. (1999) and the error bar in the upper-right corner is an estimate of the average $1 - \sigma$ measurement error, *solid squares* for M54 stars in the Sgr dSph from Brown, et al. (1999), *open squares* for field stars in the Draco dSph from Shetrone, et al. (1998).

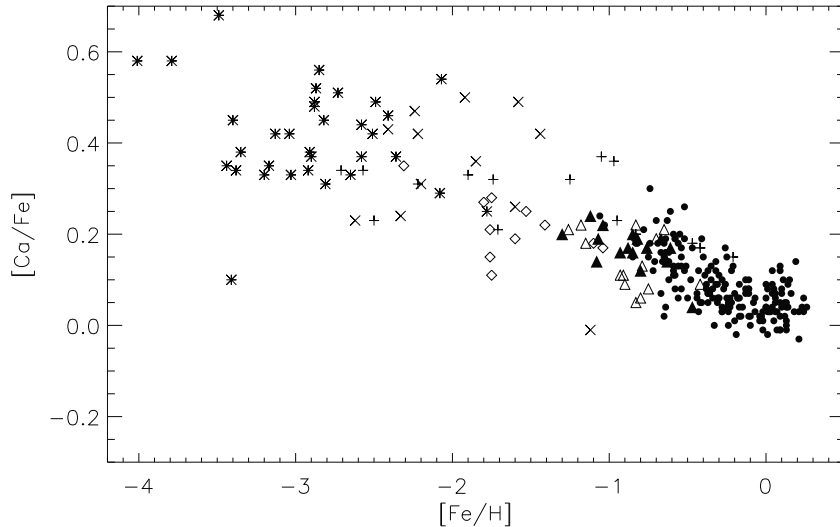


Figure 4. Calcium to iron abundance ratio as a function of metallicity for Galactic stars: *open circles* for halo stars from McWilliam, et al. (1995), *crosses* for metal-poor stars from Magain (1987), *pluses* for metal-poor stars from Gratton & Sneden (1991), *solid circles* for disk stars from Edvardsson, et al. (1993), *solid triangles* for disk stars and *open triangles* for halo stars from Nissen & Schuster (1997), *open diamonds* for stars with outer halo kinematics from Stephens (1999).

The merging history of the Galactic halo has been constrained by comparing the colors of main-sequence turnoff stars, metallicities, and the dark matter fractions of the Galaxy versus the dSphs. However, the conclusions reached by Mateo (1996) and Unavane, et al. (1996) do not agree. It is premature to apply the element ratio test until we sample a range of dSph masses and star-formation histories. However, we can say that not much of the Galactic halo could be formed from the accretion of dSphs similar to the Sgr dSph unless they merged many Gyr ago before the stars reached $[\text{Fe}/\text{H}] \approx -0.6$, because the mean metallicity of the Galactic halo is $[\text{Fe}/\text{H}] \approx -1.6$ and the $1\text{-}\sigma$ dispersion is 0.65 dex. Recent studies have found Galactic halo stars with $[\alpha/\text{Fe}] \approx +0.1$ (Nissen & Schuster 1997, Stephens 1999) similar to those found in the Draco dSph. Fullbright (1999) is performing a large survey of halo stars that will be ideal for estimating how much of the Galactic halo has element ratios this low.

The fact that the most metal-poor stars in the Sgr dSph have $[\alpha/\text{Fe}]$ nearly equal to the theoretical yield of Type II SNe and typical Galactic halo stars implies that the upper-mass end of the initial mass function (IMF) in dSphs was similar to the Galaxy's IMF. Measuring the element ratios for very metal-poor stars in dSphs, $[\text{Fe}/\text{H}] \leq -2.0$, will be crucial for determining the upper-mass end of the IMF and estimating the energy available to power galactic winds. A study of the faint end of the stellar luminosity function in the Ursa Minor dSph (Feltzing, et al. 1999) concluded that the low-mass end of its IMF was no

different than that of the globular cluster M92. Thus the IMF for dSphs may not be significantly different than the Galactic IMF.

A significant fraction of dSph stars (2 of 11 field stars in the Sgr dSph, 1 of 2 stars in M54, and 2 of 4 in Draco dSph) show signs of having altering their primordial abundances of O, Na and Al through proton burning. Sgr star #1-73 shows this most dramatically. Oxygen is depleted while Na and Al are enhanced. This self-enrichment pattern was first identified in certain Galactic globular clusters (see Kraft, et al. 1997, and references therein), although it is not observed in any Galactic field halo star (Shetrone, et al. 1996). The cause of the difference is not yet understood, but we could use this as another constraint on the merger history of the Galaxy.

By determining the ages and the chemical abundance ratios in dSphs stars we also can gain new insights into stellar nucleosynthesis by constraining the timescale on which an element is produced, and thus the masses of stars which produce it. For example, we can deduce the initial masses of the asymptotic-giant branch stars that are the major sources of s-process elements. Also, we can examine whether the trend in $[Al/Fe]$ verses $[Fe/H]$ for Galactic field stars is driven by secondary production of Al or by a metallicity-dependent yield.

5. Conclusion

Through detailed studies of the ages and chemical abundances of the stellar population of dSph galaxies we will learn a great deal about stellar nucleosynthesis, the physical processes that regulate star formation, dwarf galaxy evolution, and the merging history of our own Milky Way.

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